LIMITED INVESTIGATION OF AIR-TO-AIR LASER DETECTION AND RANGING
(PROJECT WALKER RANGER)

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AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
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AD INEXPLORATA

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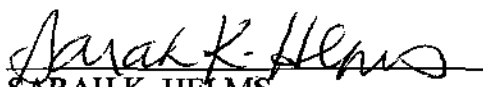
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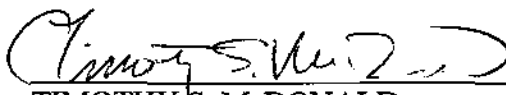BRIAN T. DEAS
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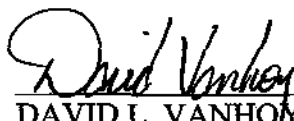Project Flight Test Engineer

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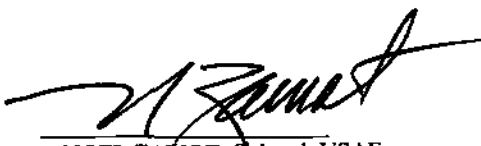Captain, USAF
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14. ABSTRACT

This report presents the results of the Limited Investigation of Air-to-Air Laser Detection and Ranging (Project Walker Ranger), a demonstration of the Advanced Scientific Concepts LADAR capabilities. The overall test objective of the Walker Ranger TMP was to demonstrate the ability of the ASC LADAR to gather an accurately ranged three dimensional image of an air-to-air target. Due to LADAR hardware issues/late delivery of a flight-qualified test item testing was limited to a single, partially successful, ground test. The Air Force Institute of Technology requested this testing.The USAF TPS, Class 09A, conducted this testing on 22 September 2009. No test objectives were met.

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EXECUTIVE SUMMARY

The US Air Force Test Pilot School (TPS) class 09A Walker Ranger test management project (TMP) group accomplished ground testing of the Advanced Scientific Concepts (ASC) laser detection and ranging (LADAR) system. The planned test consisted of a ground test and three flight test sorties. However, flight testing was not completed. Due to LADAR hardware issues, late delivery of a flight-qualified test item the TMP group was limited to a single, partially successful, ground test. The ground test succeeded in gathering LADAR determined ranges to compare to known ground target ranges. However the ground test did not succeed in gathering sufficient DGPS data for comparison.

The overall test objective of the Walker Ranger TMP was to demonstrate the ability of the ASC LADAR to gather an accurately ranged three dimensional image of an air-to-air target.

Specific test objectives are shown below:

    1. Determine the range accuracy of the ASC LADAR using differential GPS (DGPS) as the truth position source

    2. Determine a maximum target detection range against an airborne target

No test objectives were met.

The TMP ground test occurred on 22-23 September 2009. The ground test was performed on the TPS ramp and involved ground tape measurements along with DGPS and LADAR ranging between the test and target F-16s. An Air Force Flight Test Center (AFFTC) F-16D tail number 90-00797 was used as the test aircraft and F-16D tail number 87-00391 was used as a support target aircraft. The three planned flight tests were not completed.

The test configuration had the LADAR internally loaded (LIL) on the Reconfigurable Airborne Sensor, Communication and Laser (RASCAL) pod. The LIL RASCAL was loaded on weapons station three of the F-16D test aircraft. Additionally, reflective tape was applied externally to several locations on the target aircraft. Both F-16Ds were equipped with GPS aided inertial navigation reference (GAINR-LITE) systems designed to provide the required data for DGPS processing of range between the two aircraft and to serve as the test truth source. However, the test aircraft GAINR-LITE system failed to collect data during the ground test; therefore, ground measurements were used as truth data instead of DGPS processed range information.

The LADAR generated ranged images by sending out pulses of 1.57 micrometer wavelength diffused laser light. Reflections of the laser pulses off targets within a nine degree field of view were captured optically and directed onto a 128x128 pixel focal plane array. Each pixel recorded reflected intensity to generate an image, while also recording round trip time of flight of the pulse to generate target range.

During the ground test, signal returns from the target F-16 at 300 feet were not sufficient to generate a clear three dimensional image. Additionally, LADAR range measurements did not achieve the expected accuracy of three inches. Major contributors to inaccurate range measurements were return signal measurement, return signal storage, and system calibration variability.

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INTRODUCTION

This Technical Information Memorandum reports on the test management project (TMP) that sought to investigate the air-to-air ranging accuracy and maximum range capability of the laser detection and ranging (LADAR) system developed by Advanced Scientific Concepts (ASC). The system was a next generation sensor with a wide range of potential uses, one of which could be assisting with air-to-air refueling (AAR) of unmanned aerial vehicles (UAV). This project also investigated a ranging algorithm, developed by the test team, for post-processing the LADAR data to determine if the new algorithm provided improvement in range resolution.

The Responsible Test Organization was the 412th Test Wing. Testing was conducted under the USAF Test Pilot School (TPS) Job Order Number MT09A700 and was accomplished 22-23 September 2009. The Walker Ranger TMP was conducted at the request of the United States Air Force Test Pilot School in conjunction with the Air Force Institute of Technology Department of Electrical Engineering. The testing was conducted with the LADAR internally loaded (LIL) on the Reconfigurable Airborne Sensor, Communication and Laser (RASCAL) pod and loaded on F-16D test aircraft, tail number 90-00797 (figure 1). Another F-16D, tail number 87-00391, was used as a target for ranging. Flight testing was not accomplished.

Figure 1: LIL RASCAL Pod on Test Aircraft during Ground Test

Background

The LADAR system was evaluated for a wide range of military uses because of its unique capability to simultaneously image and range a target scene providing a three dimensional representation at video frame rates. Two of the potential uses of the system were three dimensional target identification and autonomous system guidance. The autonomous system guidance mission provided the basis for all testing performed under the Walker Ranger TMP.

A LADAR system, such as the ASC system used for this test, may have been able to provide guidance to a UAV during AAR operations. Autonomous UAV close formation in the AAR

position had been accomplished using differential global positioning systems (DGPS) to provide relative position with an average spherical error of 1.2 inches between the tanker and the receiver aircraft (reference 1). However, a non-GPS solution was desired to maintain autonomous capability in a GPS denied environment.

Target ranging against a known-range target had not been accomplished with this system prior to this TMP. Range accuracy of the LADAR was determined by ASC to be approximately three inches; however this determination was made in a laboratory using fiber optics. Additional investigation was done to evaluate the relative ranging errors of the system. For the purposes of this test, the term relative range referred to the range measured between two objects in the target scene. Relative range was different from absolute range which was defined for this test to be the range from any point in the target scene to the LADAR receiver itself. Open air range comparisons between LADAR generated ranges and accurately ranged truth sources had not yet been evaluated.

Test Item Description

Physical Description

The ASC LADAR under evaluation for this test consisted of four major components: a laser transmitter, a laser receiver focal plane array with interchangeable optics, a visible spectrum television (TV) camera, and a computer loaded with appropriate software to operate the system. The uninstalled system was six inches wide by eight inches tall by eleven inches deep and is shown in figure 2 (reference 2).
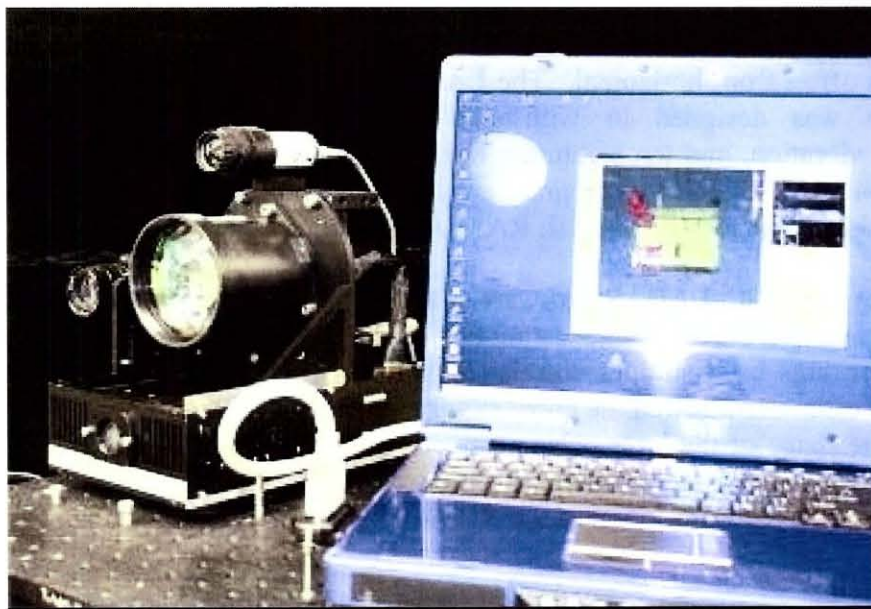
Figure 2: Uninstalled LADAR System (reference 2)
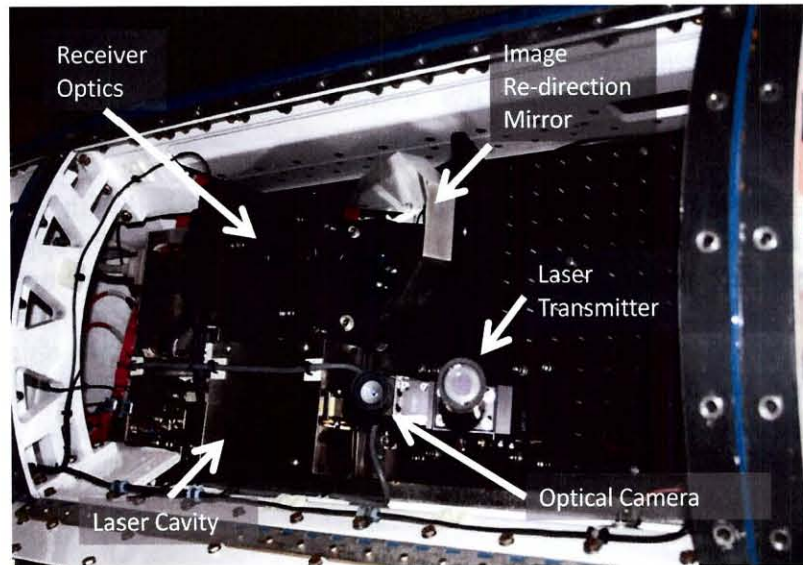
Figure 3: LADAR Internally Loaded RASCAL (LIL RASCAL)
(reference 3)

The laser transmitter generated pulses of 1.57 μm light at a peak power of 18 mJ (reference 2). The pulses were then diffused to ensure they covered the field of view (FOV) of the receiver. The receiver optics were designed to be interchangeable, but an 85 mm lens with a nine degree FOV was the sole setup for this test. The TV camera provided a secondary visual reference for the target scene and had a FOV of approximately twenty degrees.

The LADAR components were mounted in the RASCAL pod with a down and aft look angle sixty degrees offset from horizontal. The LADAR internally loaded RASCAL (LIL RASCAL) configuration was designed to withstand the RASCAL flight environment to include acceleration, vibration, and temperature. The RASCAL flight environment was established by the TPS SENIOR RASCAL test program and is documented in the *Certification Data Package, RASCAL Pod-7* (reference 4). The LIL RASCAL assembly is shown in figure 3.

In addition to the ASC LADAR software, the Walker Ranger team developed a normalized variable shaping (NOVAS) range estimation algorithm to post-process the data. Previous LADAR algorithms used straight correlation with a predetermined or optimized pulse shape. The NOVAS estimator allowed the correlation reference pulse to vary in shape and symmetry to best match the shape of the laser pulse received by the detector. The intent of NOVAS was to compensate for error due to various physical interactions within the laser cavity as well as with the target shape. A full description of the NOVAS algorithm is contained in appendix B.

System Operation

For each pulse sent by the LADAR, an image was created of all objects in the FOV. Each pixel in the array recorded the intensity and time history of the laser energy reflected by the target. The intensity values built the image scene while the time history built the range to the target based on the round trip time of flight of the laser pulse.

The camera operated in two modes: trigger mode and staring underwater laser ranging (SULAR) mode. Trigger mode was the normal operating mode while SULAR mode was designed to overcome target obscuration from semi-transparent substances such as water, smoke, or haze. The difference was the method of commanding return pulse data to be saved. After a laser pulse was sent out in trigger mode, each pixel waited to record data until a certain user defined threshold of energy was received. Once the threshold was crossed, the pixel saved a rough distance to the target as well as 20 intensity values separated by approximately 2.5 ns to capture the target return pulse waveform. Each pixel operated independently until a user defined time had elapsed, at which point pixels that had not received a target return pulse recorded a default value. In SULAR mode, all pixels in the array recorded data at the same time, starting at a user defined time interval. Only returns from targets inside this range "gate" were recorded by the LADAR. Pixels without a target in the range gate recorded background radiation only and no actual laser energy. A more detailed description of these modes is contained in appendix B.

Test Objectives and Limitations

The overall test objective of the Walker Ranger TMP was to demonstrate the ability of the ASC LADAR to gather an accurately ranged three dimensional image of an air-to-air target.

Specific test objectives are shown below:

1. Determine the range accuracy of the ASC LADAR using differential GPS (DGPS) as the truth position source

2. Determine a maximum target detection range against an airborne target

Neither test objective was accomplished.

Originally, the LADAR was scheduled to be delivered by the contractor on 1 August 2009. Significant technical challenges and sub-contractor scheduling led the contractor to slip the delivery date of the LIL RASCAL pod numerous times. The system suffered several delays due to technical issues with system hardware and design compatibility. These technical delays forced the contractor to miss the scheduled vibration test, a prerequisite for flight certification, and ultimately prevented flight test of the LADAR within the test window.

TPS student scheduling requirements, vibration test availability, and TMP deadlines allowed a minimal 24 hour period to accomplish the ground test. This forced the test team to accept a rushed acceptance test, ground check, electro-magnetic interference and compatibility test (EMI/C), and ground data timetable. Additionally, the LIL RASCAL used for the ground test had not been cleared for flight.

Separate ground checks and EMI/C that were planned to be accomplished prior to ground test data collection were eliminated to prioritize data collection. This required the test team to troubleshoot system problems while collecting ground data. During an eight hour ground test window, five hours were spent investigating system problems that included no cockpit multi-

function display (MFD) video, no ability to control the LADAR from the cockpit via the ECM C-9492, and no ability to control RASCAL from the OQO™ palmtop computer.

Ultimately, the test program was only able to collect three hours of ground data from a non-flight worthy LIL RASCAL pod instead of three test flights.

TEST AND EVALUATION

Test Execution

The test aircraft (F-16D 90-00797) and target aircraft (F-16D 87-00391) were parked on the TPS ramp separated by a distance of 335 feet. Both aircraft used ground power, and GPS aided inertial navigation reference (GAINR-LITE) systems were used to collect DGPS distance data. DGPS data were collected for the required duration of one hour for the target aircraft only. DGPS data for the test aircraft were only gathered for 90 seconds due to a system malfunction. The original intent for the DGPS data was to determine the mean and standard deviation of DGPS range between the GAINR-LITE systems to compare against the 412 TW/ENR stated position accuracy for the GAINR-LITE of 1.5 feet. Insufficient data were collected to address potential drift of the system positions. Further ground testing will be required prior to flight test to ensure accurate range results for comparison to LADAR flight test ranging. **Verify mean and standard deviation of GAINR-LITE meet predictions from 412 TW/ENR prior to flight test of the LIL RASCAL. (R1)** [1]

The LADAR system was installed in the RASCAL pod and the pod was mounted on station 3 of the test aircraft. The LADAR system was configured in the pod to image targets at a 60 degree angle aft and downward of the pod through a polycarbonate viewing window. For the ground test, an adjustable mirror was positioned below the RASCAL pod viewing window such that laser energy pulses were projected parallel to the ground to view targets in front of the test aircraft. Figure 4 illustrates the RASCAL pod, LADAR system, and adjustable mirror setup used to complete the tests.
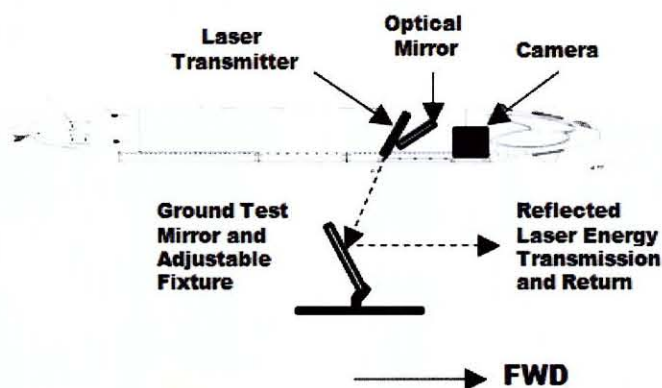
Figure 4: Ground test setup with LIL RASCAL and adjustable ground test mirror

A series of reflective targets were then placed in front of the test aircraft at known positions and ranges along the ground. The reflective targets consisted of small wood blocks with dowel rods protruding from the blocks and a small reflective flag attached to the end of the dowel. The reflective flags were sized to minimize saturation of individual image pixels for later post-

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[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report. (The Author's Guide to Writing Air Force Flight Test Center Technical Reports, reference 5)

processing. Figure 5 shows a schematic of the reflective flag layout placed in front of the test aircraft for imaging. The layout was designed such that the reflectors would appear evenly spaced on a horizontal line in the LADAR image. The target aircraft was located on the center line near the 300 foot target but is not shown in figure 5 for clarity. Also not shown in figure 5 are targets at 201, 202, 203, and 204 feet in the vicinity of the 200 foot target. Figure 6 shows a photograph of the test aircraft viewing the reflector flag array and the target aircraft used for LADAR range ground tests. Figure 7 shows a typical LADAR image of the target array captured during the ground test. See appendix A for additional similar images.
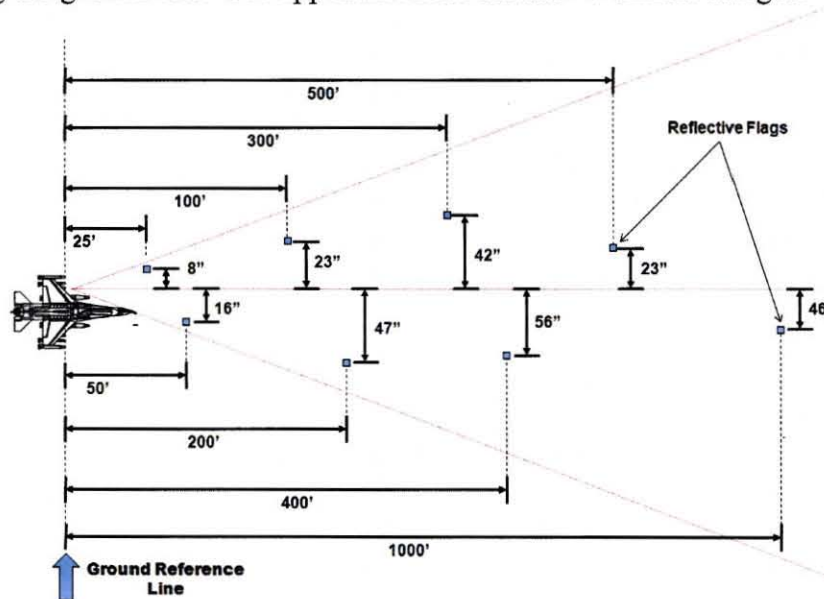
Figure 5: Ground test setup depicting reflective target layout (for clarity, the target aircraft is not shown in position near the 300 foot target)

Figure 6: Photograph of the ground test setup

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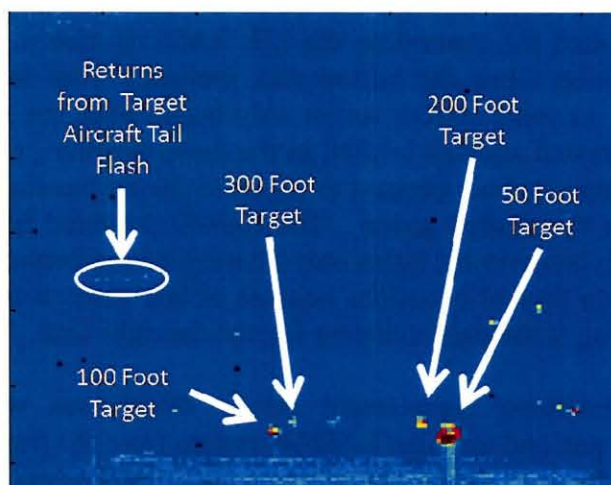
Figure 7: Typical LADAR image captured during the ground test

Results and Analysis

Results from the ground test are broken down into five separate topics for discussion. The first section addresses the overall system integration of the LIL RASCAL. The second section addresses the precision and accuracy of the range results reported by the LADAR to provide a statistical basis for further analysis. The third section addresses the effects of timing system variability on the range measurements. The fourth section focuses on the compatibility of the LADAR output and the signal processing methods used by the NOVAS algorithm. The fifth and final section discusses some aspects of the total system performance in relation to utility for future flight research, development, test, and evaluation.

System Integration

The LIL RASCAL was not well integrated with the test aircraft during the ground test. The LIL RASCAL failed to display video on the F-16 MFD during all system operations. The cockpit operation with the ECM C-9492 and OQO™ palmtop computer were ineffective for LIL RASCAL control.

When the LIL RASCAL was mated to the F-16D, the LADAR video source was connected to an AGM-65 Maverick video input so that LIL RASCAL images could be assessed in real time on the cockpit MFD. An incompatibility between the signal output from the LIL RASCAL and that required by the aircraft prevented video from being displayed on the F-16 MFD, making it impossible for the test team to monitor the system from the cockpit. During the ground test, an external monitor, keyboard, and mouse were attached directly to the RASCAL to monitor and control the LADAR system. This solution worked on the ground but was unusable for flight. Additionally, the OQO™ screen resolution was too low and the screen size was too small to provide useable airborne feedback. Feedback to the pilot of LIL RASCAL operation was unsatisfactory. **Provide video from the LIL RASCAL to the F-16 MFD to allow assessment in real time of LADAR operation. (R2)**

The pilot controlled the RASCAL through the ECM C-9492 control panel (figure 8). This control unit was poorly suited for controlling the LIL RASCAL due to the button design that latched in the down position when the button was pressed. This led to difficulties when commanding the LADAR because system action only began after the return/up stroke of the button. If a button was pressed and left latched in the down position, no system response was initiated. Even if the button was later pressed to return to the up position, the RASCAL would only occasionally perform the desired action. The C-9492 provided limited system feedback through lights on the panel; however the lights only illuminated momentarily. These indications were missed by the pilot on several occasions because of sun glare, a finger remaining on the button, or simply not looking at the right indicator light at the right time.

AFFTC Modification Operational Supplement (MOS) 09-01 was written specifically for operation of the RASCAL pod and installed LADAR system from the front cockpit of the F-16D test aircraft. MOS 09-01 focused on the operation of the ECM C-9492 panel and viewing the LADAR returns (using AGM-65 video feed) on the front cockpit MFD. The MOS was originally written based on inputs from both in-house engineers at Test Pilot School and the prime contractor (ASC) who had worked together to integrate the RASCAL pod and LADAR system to the F-16D systems. The MOS, when used during ground test, proved not to be useful and was unsatisfactory for use in any flight test. The deficiencies with the MOS were primarily due to two inter-related factors: (1) the ECM C-9492 panel did not physically operate in the manner originally desired to provide necessary feedback to the pilot with respect to LADAR system operation and (2) the language in the MOS did not accurately reflect the actual operation of the RASCAL pod and LADAR system via the ECM C-9492 panel. Several RASCAL pod systems and LADAR functions were intended to be controlled by either pressing/releasing or pressing/holding/releasing buttons on the ECM C-9492 panel. For example, the LADAR initialization function used prior to imaging targets was intended to be controlled by pressing the appropriate button on the ECM panel for the initialization, holding the button for three seconds, then releasing the button. This would allow an internal circuit to be closed for three seconds while the button was held pressed down and allow adequate time for the LADAR system to complete its initialization process. However, once the button was released, the circuit would be broken and the initialization process would discontinue. The ECM C-9492 panel was not mechanized in this fashion, however. In fact, once a button on the panel was pressed down, it remained locked in the down position until the button was subsequently pressed a second time to release it from the down position. Further, it was intended that the panel would provide some visual feedback that something had occurred in the system (such as a light illuminating when the circuit was closed). No visual feedback to the pilot in the front cockpit occurred; neither the ECM C-9492 panel nor the MFD gave any indication of any system actuation during ground test. These facts were neither known nor considered prior to the original writing of the MOS and ground testing, causing a large amount of confusion during test execution. The compressed schedule that forced system integration testing and ground testing to be performed simultaneously did not allow adequate time to correct the problem. The MOS did not provide adequate information to the pilot and could not be used in the flight test environment in its current form. Cockpit control of the LIL RASCAL was not well defined, not intuitive and unsatisfactory. **Provide an alternate interface or control panel and accurate written instructions to operate the LADAR system in the RASCAL pod. (R3)**
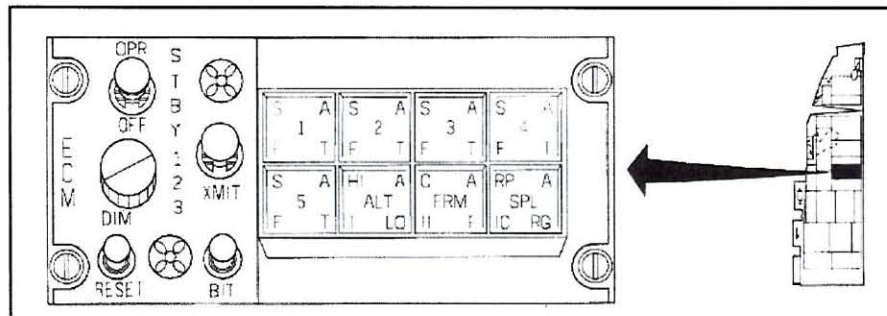
Figure 8: ECM control panel C-9492; left console
(from T.O. 1F-16CM-34-1-1, reference 6)

Accuracy and Precision of Reported Range Results

The LADAR did not achieve expected range accuracy against stationary ground targets. Based on published documents from the contractor, the reported ranges from the LADAR were expected to be within three inches of the actual range (reference 2). The standard deviation of range measurements taken during the ground test indicated the expected range accuracy was not met.

A summary of LADAR generated ranges collected during the ground test is shown in table 1. Some of the ranges were collected against the prepositioned reflective targets of known range, while others were targets of opportunity of unknown range. Targets that appear more than once in the table indicate a different algorithm was used to estimate the range to the same target. Each line in the tables represents a single pixel used to generate the range estimation. The same target returns captured by the LADAR were analyzed by two different algorithms for estimating range. The range estimations in table 1 were generated with the NOVAS algorithm and the range estimation algorithm internal to the contractor provided LADAR control software. The ASC algorithm was similar to the NOVAS algorithm in concept, but was different in implementation as described in appendix B.

A sample of thirty images was used to generate thirty range estimations for each of the targets shown in table 1 using both the NOVAS algorithm and the ASC algorithm. The sample mean and standard deviation for each set of target measurements is provided in the table. A confidence interval for the LADAR system's population mean of range to each target is provided for 95 percent certainty. Recall the confidence interval is given by the equation

$$X \pm t_{n-1}(\alpha/2)\frac{s}{\sqrt{n}}$$

where X is the sample mean, s is the sample standard deviation, n is the number of data points in the sample, $t_{n-1}(\alpha/2)$ is the Student's t-distribution for $n-1$ degrees of freedom and $(1-\alpha)$ overall certainty. A confidence interval is a range in which the mean of a population lies within a given certainty.   An increase in samples affects the width of the interval, typically reducing the width. The confidence interval in this test represents a 95 percent probability that the mean of the

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LADAR estimated ranges lies within the interval. Ideally, the confidence interval should encompass the actual range. Cases that showed an actual range outside of the confidence interval indicated an absolute LADAR range error.

A prediction interval is a range from which the next sample will come within a given probability. The larger the variability in sample set, the larger the prediction interval. The prediction interval is typically larger than the confidence interval. Prediction intervals for 95 percent certainty are provided for LADAR range measurements of each target, implying 95 percent probability that the next LADAR measurement of the target will fall within the provided interval. The prediction interval is given by

$$X \pm t_{n-1}(\alpha/2)s \sqrt{1 + \frac{1}{n}}$$

The LADAR measurements for a single pixel exhibit a variability that follows a normal distribution. See sample normal probability plots of range estimations from both algorithms in figures 9 and 10.
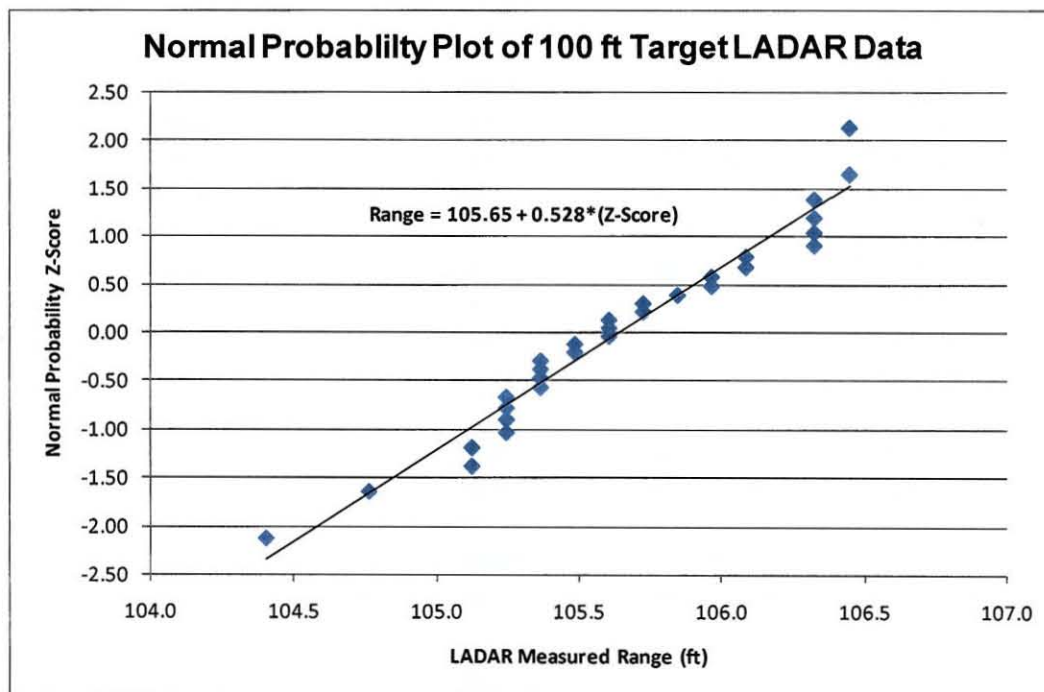

Figure 9: Normal probability plot of 30 LADAR measurements from reflective target "One Hundred" using the NOVAS algorithm
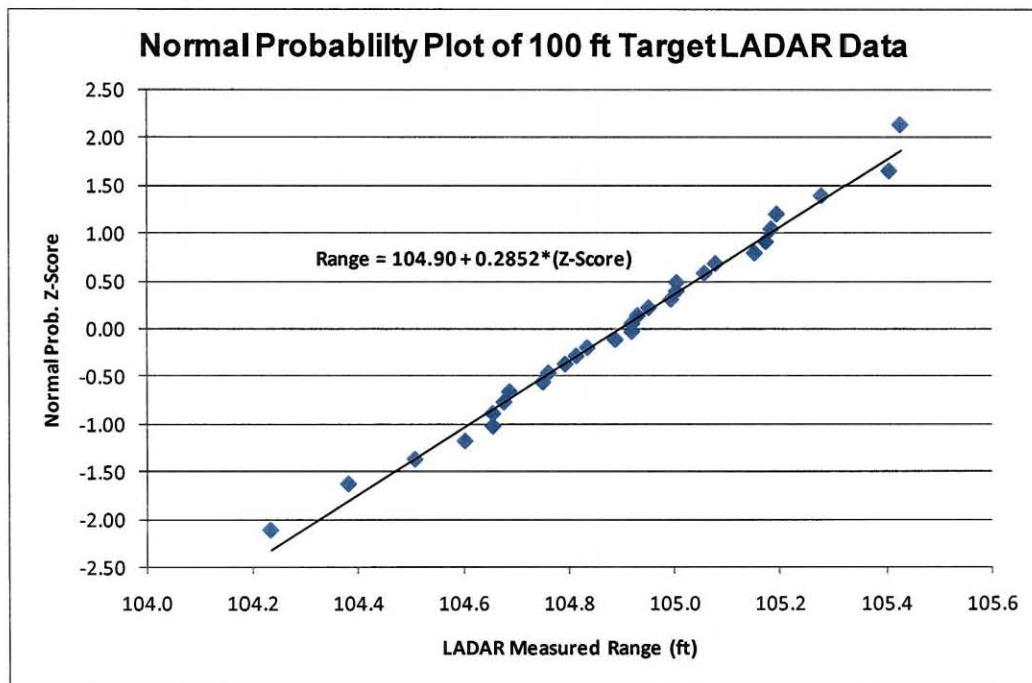
Figure 10: Normal probability plot of 30 LADAR measurements from
reflective target "One Hundred" using an ASC-developed ranging algorithm

Inspection of table 1 shows that the actual range to each target does not always fall inside the
confidence intervals for the population mean of LADAR range measurements. Additionally, the
actual range only occasionally falls within the prediction intervals for the next measured
samples. Confidence and prediction intervals that contain the actual target range are shown
circled in green in table 1. This implied that a deficiency in the LADAR equipment and system
likely existed regardless of the estimation algorithm used.

Target Codename	Actual Target Range (ft)	LADAR Measured Range (n=30)		95% Confidence Interval		95% Prediction Interval		
		Mean (ft)	Std. Dev. (ft)	Lower Limit (ft)	Upper Limit (ft)	Lower Limit (ft)	Upper Limit (ft)	
Fifty	55.6	55.3	0.5	55.1	55.5	54.2	56.4	NOVAS Algorithm
One Hundred	105.6	105.9	0.4	105.8	106.1	105.2	106.7	
Two Hundred	205.6	205.9	0.5	205.7	206.1	204.8	206.9	
Two Hundred One	206.6	205.0	0.7	204.7	205.2	203.6	206.4	
Two Hundred Four	209.6	207.9	0.5	207.7	208.1	206.8	208.9	
Three Hundred	305.6	305.6	0.3	305.5	305.7	304.9	306.3	
Fifty	55.6	54.5	0.2	54.4	54.5	54.1	54.8	ASC Algorithm
One Hundred	105.6	104.9	0.3	104.8	105.0	104.3	105.5	
Two Hundred	205.6	206.3	0.3	206.2	206.4	205.7	206.9	
Two Hundred One	206.6	200.1	0.7	199.9	200.4	198.7	201.6	
Two Hundred Four	209.6	202.3	0.6	202.1	202.6	201.1	203.6	
Three Hundred	305.6	305.7	0.3	305.6	305.8	305.1	306.3	

Table 1: LADAR range measurements and 95% confidence & prediction intervals
compared to truth values using the NOVAS and ASC algorithms

Overall, the ASC LADAR proved to be inaccurate. The overall root mean squared error
(RMSE) for range estimations against range known targets was 8.9 inches. However, the range
estimation error was dependant on target range. Figure 11 shows the RMSE individually for the

50, 100, 200, and 300 foot targets. It could be seen that there was a direct relationship between target range and range estimation RMSE. What could not be determined from the data collected was the nature of the relationship. The implication of the linear fit was that there was some optimized range—in this case approximately 350 feet—where the error was zero. Beyond this range the error would continue to grow linearly. More testing with targets beyond 400 feet must be accomplished to determine the relationship between target range and range estimation error. **Accomplish testing of the ASC LADAR with targets at ranges 400 feet and beyond. (R4)**

Most importantly, however, was the fact that the error at close ranges also grew to unacceptable levels. Estimations held that the target F-16 would only be clearly visible once inside 200 feet of range where the range estimation error was approximately eight inches. Additionally, any future application to aerial refueling of an unmanned vehicle would suffer greatly from the decrease in accuracy that occurred at short range.
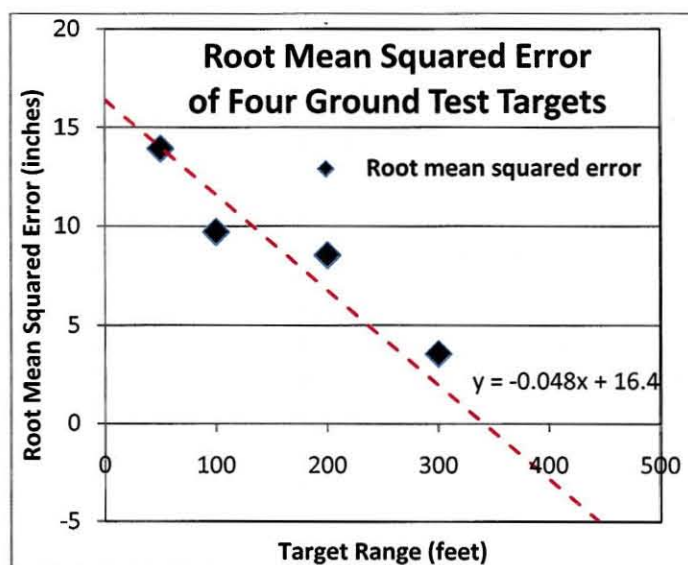
Figure 11: Root mean squared error of estimated range to four ground test targets

Effect of Timing System Variability on Range Results

The most likely source of error in the range estimations was the timing system variability in the LADAR system. The oscillator controlling the timing clock operated at a nominal 400 mega-Hertz (MHz) and thus the system was designed to count time slices at intervals of 2.5 nanoseconds (ns) (reference 2). A single time slice was therefore equivalent to 1.2295 feet of range. However, it was observed that the oscillator varied in frequency, changing the time interval and therefore changing the range attributed to each time slice. For example, an oscillator operating at 410 MHz would count 81.3 time slices for a target at 100 feet. If the ranging algorithm were calibrated to 400 MHz, it would report these 81.3 time slices as 97.5 feet. In addition, from the time the initial laser pulse fired, an unknown time period on the order of nanoseconds passed before information was recorded resulting in an unknown bias of

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approximately 8 to 12 feet. A calibration was intended to reduce the bias error and correct the algorithm to use the same oscillation frequency of the camera at the time of data collection.

The NOVAS algorithm was calibrated using the collected data set. The first step was to find the average oscillator frequency of the camera. A set of 30 measurements to each of the targets placed at 100 and 200 feet were used. An oscillator frequency was calculated to make the average reported relative range between these two targets equal to 100 feet. The second step was to remove the bias. A set of 30 measurements to each of the targets at 100, 200, and 300 feet were used. The average range error reported by the algorithm to all of the targets was attributed to the bias and removed from all subsequent measurements. The average clock frequency used for the data analysis was 410 MHz, with an average offset bias of 5.82 feet.

The contractor provided estimation algorithm calibration worked on the same principle, but was much more limited in application. Within this software, the calibration routine was based on a single measurement to two of the known range targets. It also calculated the oscillator frequency based on the known relative range between the targets and subsequently removed the bias based on the absolute ranging error to both the targets. The oscillator frequency used by the contractor provided algorithm was 406 MHz with an offset bias of 8.53 feet.

The limitation of the ASC calibration arose from the variability in range measurements from the LADAR. In the previous section it was shown that any single measurement from the LADAR had a 95 percent chance of being within approximately 8 inches of the actual value. Therefore it was reasonable that the measured relative range between two LADAR data points could have had as much as a 1.3 foot error between them. This would induce up to a 1.3 percent ranging error for the test in which a 100 foot relative range was used to calibrate the algorithm, but up to a 5.2 percent error if the minimum range of 25 feet recommended by ASC was used to calibrate the algorithm (reference 3).

Table 1 contains evidence that the NOVAS algorithm with an averaged calibration slightly outperformed the contractor algorithm with a single point calibration. However, the overall poor range accuracy could be attributed to the fact that the varying frequency of the oscillator made any calibration invalid for any LADAR data except for those data used to create the calibration. In order to calibrate the LADAR for a given scene, two objects in that scene must be at a known range from the LADAR itself. This makes this system inaccurate for an operational use requiring range accuracy. Some potential solutions would have been to improve the system oscillator, add a system to monitor the oscillator frequency, or by use of fiber optic cables, provide two known-range targets to two of the pixels on the imaging array, allowing a calibration to be performed for every LADAR image. **Implement compensation for the system clock variability. (R5)**

Signal Processing Analysis

The method the ASC LADAR used to capture the laser return pulse waveform affected the accuracy of pulse shape correlation algorithms like the NOVAS algorithm. The NOVAS algorithm, like most matched filter range estimation algorithms, used correlation techniques to match the shape of the return pulse. A key feature of the NOVAS was to match the left and right halves of the return pulse separately. The logic used by the ASC LADAR often truncated the

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right half of the return pulse greatly reducing the advantage the NOVAS may have over other algorithms.

The ASC LADAR trigger logic waited until the received energy exceeded a certain threshold then recorded the 12 time slices prior, the 7 time slices after, and a single marker slice at the end. The marker slice was set to zero and used as a reference for determining range. Inserting the marker slice corrupted the slices just before and just after the marker slice, making the useable waveform only 17 slices long. Because the pulse always triggered on the leading edge, the recorded pulse was usually shifted to the right of the frame and was often truncated immediately after the peak. Often the right half of the pulse was not captured and therefore could not be used as part of the shape correlation. See appendix B for a detailed explanation of this process and the specific effect it had on the NOVAS estimator as well as other well known correlation methods.

If the trigger logic were modified such that it recorded fewer frames before the trigger point and more frames after the trigger point, more of the waveform would be captured. Capturing the entire rise and fall of the waveform would improve the ranging accuracy of the any pulse shape correlation algorithm, including the NOVAS estimator. **Change the trigger logic of the ASC LADAR such that it captures the entire rise and fall of the return laser waveform. (R6)**

System Performance Analysis

The LIL RASCAL was incapable of accurately ranging a fighter type aircraft at operationally representative ranges. The configuration did not have the capability to accurately range an F-16 target at 300 feet at ground test conditions. Even with the aircraft presenting perpendicular surfaces for maximum reflection, the skin return was barely above the level of the ambient noise. In trigger mode, the returns from the aircraft were below the set threshold and were not captured at all except for a few returns from the slightly more reflective tail flash, as seen in figure 7.

In SULAR mode, which has no threshold, the aircraft was clearly visible when viewed from an intensity standpoint, but only because of the uniformity of the intensity of returns from the aircraft. The relatively constant intensity returns from the aircraft provided contrast against the noisy background even though the actual intensity of the returns is only slightly greater than the background. Notice in figure 12, in which return intensity is indicated by color, that the background contains the same intensity levels as the aircraft return, but the uniformity of the returns from the aircraft allow the image to be perceived. The effect this had on the ranging algorithm was that the aircraft could not be distinguished from the background, and became lost in a cloud of noisy range spikes as seen in figure 13. This indicated that reducing the threshold level in trigger mode would not improve the imaging of the aircraft, as it would allow a prohibitive amount of noise to be recorded.
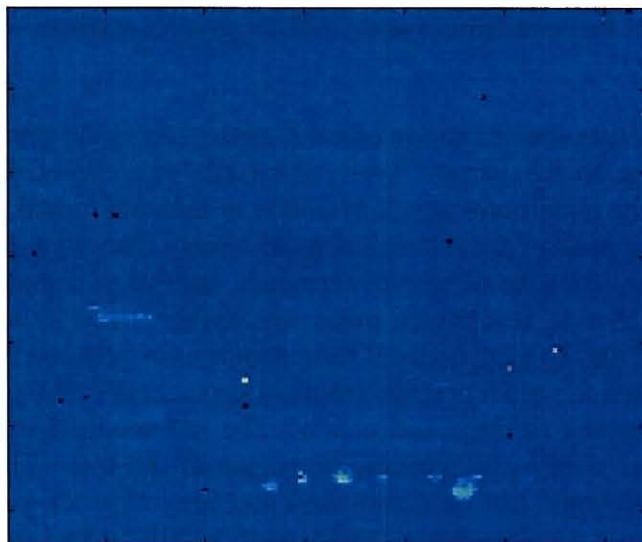
Figure 12: Image showing relative intensity of recorded laser energy by
each pixel in a single LADAR return captured in SULAR mode
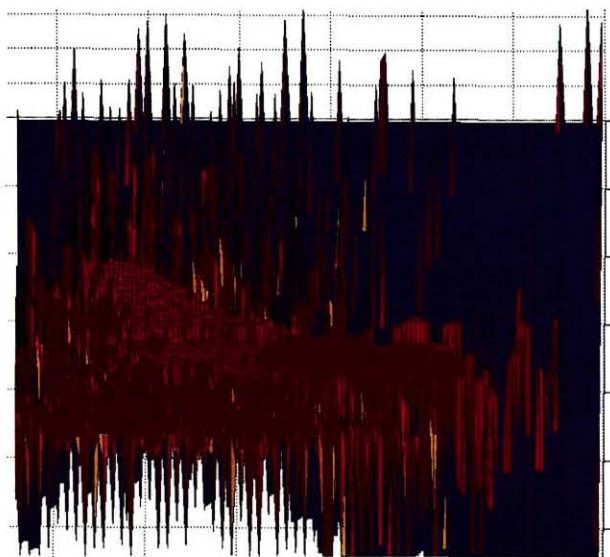
Figure 13: Three dimensional image of ranged pixels from the same
LADAR return shown in figure 12

The maximum range performance was limited by the amount of laser energy recorded by the
detector. This could have been due to laser peak power output, laser attenuation through the
RASCAL lower window, detector sensitivity, attenuation or scattering from the ground test
mirror, or LADAR settings. While the LADAR was set for nominal operation, there were ways
to increase the gain and sensitivity of the system that would increase the maximum range. The
limited time available did not allow for adjustment to these settings and as such a full exploration
of the maximum range was not accomplished. A complete analysis of the effect of these settings
may result in a larger maximum range against an F-16 target. **Perform a ground test analysis**

to characterize the affect test conditions and LADAR system settings on LADAR maximum range. (R7)

While too little energy return limited the maximum range, too much energy return limited the ability to accurately range to the target. LADAR returns that exceeded approximately 3500 digital counts surpassed the maximum current available to each individual detector, resulting in a saturated return. The true peak of the return had more energy than what could be recorded, and the true shape of the return waveform was not captured. Instead of a sharply peaked pulse with well defined slope on each side, a saturated pulse was characterized by a sharp rise, a plateau-like top, and a jagged fall off. See appendix B for a comparison between the return types. Since the NOVAS estimator used the precise range information carried in the peak of the return, this saturation limited the accuracy of range estimation. The saturated pulse flattened out the peak which became ambiguous within the plateau-like region at the top. The true target location within the saturated pulse could not be determined and ranging error was increased by up to several feet. This became a problem when targets were within 50 feet of the LIL RASCAL or too highly reflective.

The combined effect of saturated pulses and small maximum range highlighted the limited window of range and reflectivity where the LADAR provided optimal range information. This region where targets return enough energy to be accurately ranged without saturating the detector will be a very restrictive limitation on future flight test. Without improvement, system limitations discovered during this ground test would require targets to be highly optimized, restricting flexibility. **Improve the characteristics of the ASC LADAR such that targets can be accurately ranged at longer distances while close targets do not saturate the detector. (R8)**

CONCLUSIONS AND RECOMMENDATIONS

Overall, the laser detection and ranging (LADAR) internally installed reconfigurable airborne sensor, communications and laser (LIL RASCAL) system did not achieve expected range accuracy against static ground targets and would be unsuitable for ranging to airborne targets in the tested configuration.

In-cockpit system control and monitoring was unsatisfactory. The ECM C-9492 control panel in the F-16D cockpit used to operate the LADAR system in the RASCAL pod was found to be unsuitable in ground operations. The control panel was not intuitive for operating the system based on the design of the buttons used. The modification operational supplement (MOS) providing instruction for operation of the LIL RASCAL was inaccurate and unclear. The LIL RASCAL was designed to present imaging in real time to the operator in the cockpit through the cockpit multi-function display (MFD), but this feature was not demonstrated in the ground test due to system integration issues.

The LADAR did not achieve expected range accuracy. Confidence intervals and prediction intervals for individual target ranges computed from the ground test results rarely encompassed the actual truth range to the target. The total root mean squared error (RMSE) of range measurements from the LADAR was 8.9 inches. However, RMSE was dependant on range with a worst case RMSE of 13.9 inches at 50 feet and insufficient data to predict performance outside of 300 feet.

Timing system variability of the LADAR system was unsatisfactory. Two forms of calibration were used to compensate for the variability: a single point calibration employed by the contractor provided software, and a 30 point calibration employed by the normalized variable shaping (NOVAS) estimator developed by the test team. Both calibrations attempted to overcome variability in the system oscillator frequency which ultimately determined the target range. Neither method was able to compensate for the fact that essentially every image needed a separate calibration, requiring two targets of known range to be present in the image.

The method the ASC LADAR used to capture the laser return pulse waveform affected the accuracy of pulse shape correlation algorithms like the NOVAS algorithm. A key feature of NOVAS was to match the left and right halves of the return pulse separately. The logic used by the ASC LADAR often truncated the right half of the return pulse greatly reducing the advantage NOVAS may have over other algorithms. If the trigger logic were modified such that it recorded fewer frames before the trigger point and more frames after the trigger point, more of the waveform would be captured. Capturing the entire rise and fall of the waveform would improve the ranging accuracy of pulse shape correlation algorithms like NOVAS.

The configuration did not have the capability to generate a clear, ranged image of an F-16 at 300 feet during the ground test. Even with the aircraft presenting perpendicular surfaces for maximum reflection, the skin return was barely above the level of the ambient noise. In trigger mode, the returns from the aircraft were below the set threshold and were not captured at all except for a few returns from the slightly more reflective tail flash. In SULAR mode, which has no threshold, the aircraft was visible when viewed from an intensity standpoint, but only because

of the uniformity of the intensity of returns from the aircraft. It was not possible to separate range information from the background noise.

The maximum range performance was limited by the amount of laser energy recorded by the detector. This could have been due to laser output, laser attenuation through the RASCAL lower window, detector sensitivity, attenuation or scattering from the ground test mirror, or LADAR settings. While too little energy return limited the maximum range, too much energy return limited the ability to accurately range to the target. Since the NOVAS estimator used the precise range information carried in the peak of the return, this saturation limited the accuracy of range estimation. True target location within a saturated pulse could not be determined and ranging error was increased by up to several feet. The combined effect of saturated pulses and small maximum range highlighted the limited window of range and reflectivity where the LADAR provided optimal range information. This region where targets return enough energy to be accurately ranged without saturating the detector will be a very restrictive limitation on future flight test.

The above conclusions led the Walker Ranger team to make the following recommendations in priority order:

- **Provide video from the LIL RASCAL to the F-16 MFD to allow assessment in real time of LADAR operation. (R2, page 8)**

- **Perform a ground test analysis to characterize the affect test conditions and LADAR system settings on LADAR maximum range. (R7, page 17)**

- **Verify mean and standard deviation of GAINR-LITE meet predictions from 412 TW/ENR prior to flight test of the LIL RASCAL. (R1, page 6)**

- **Implement compensation for the system clock variability. (R5, page 14)**

- **Improve the characteristics of the ASC LADAR such that targets can be accurately ranged at longer distances while close targets do not saturate the detector. (R8, page 17)**

- **Change the trigger logic of the ASC LADAR such that it captures the entire rise and fall of the return laser waveform. (R6, page 15)**

- **Provide an alternate interface or control panel and accurate written instructions to operate the LADAR system in the RASCAL pod. (R3, page 9)**

- **Accomplish testing of the ASC LADAR with targets at ranges 400 feet and beyond. (R4, page 13)**

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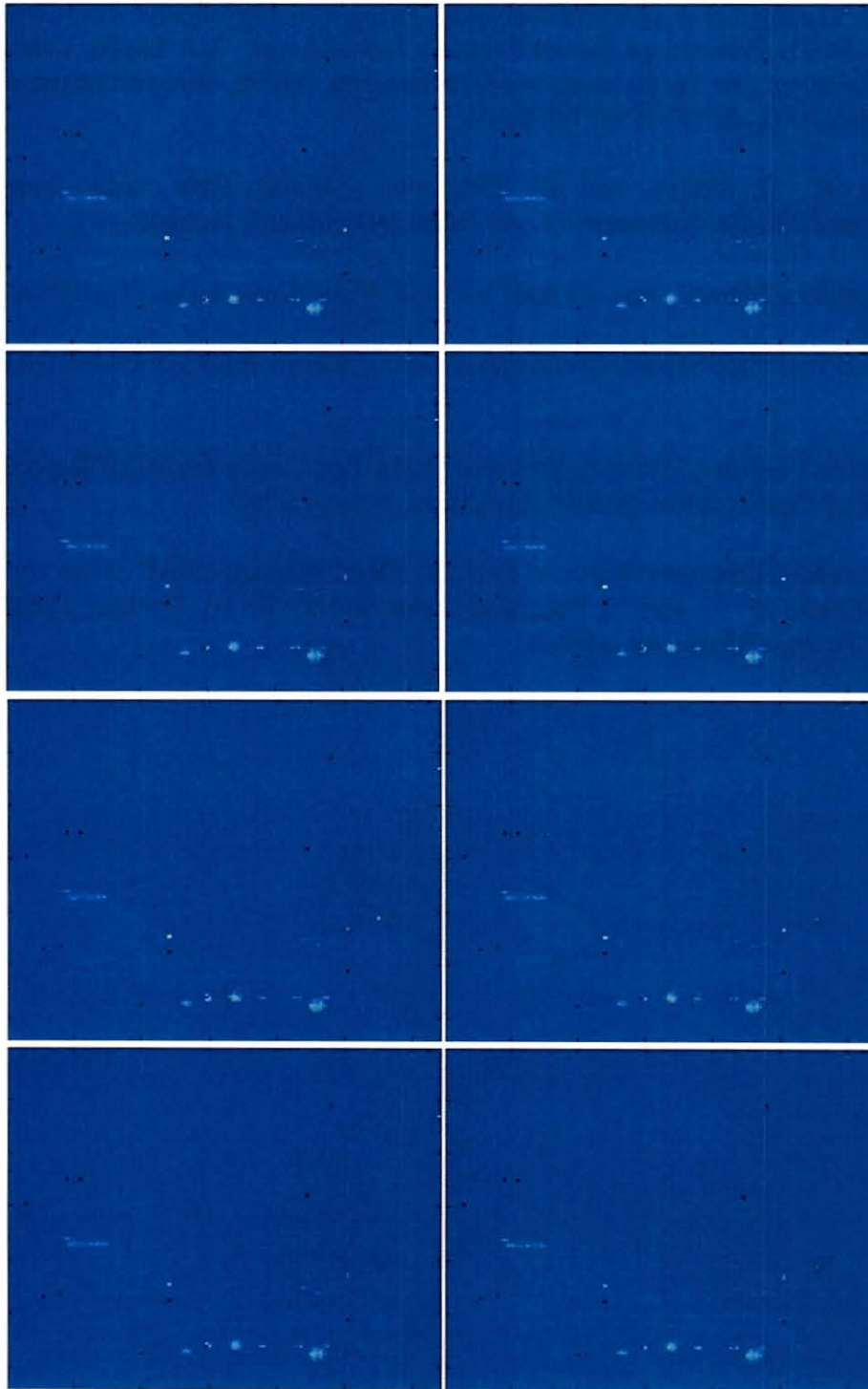
APPENDIX A - TYPICAL LADAR IMAGES

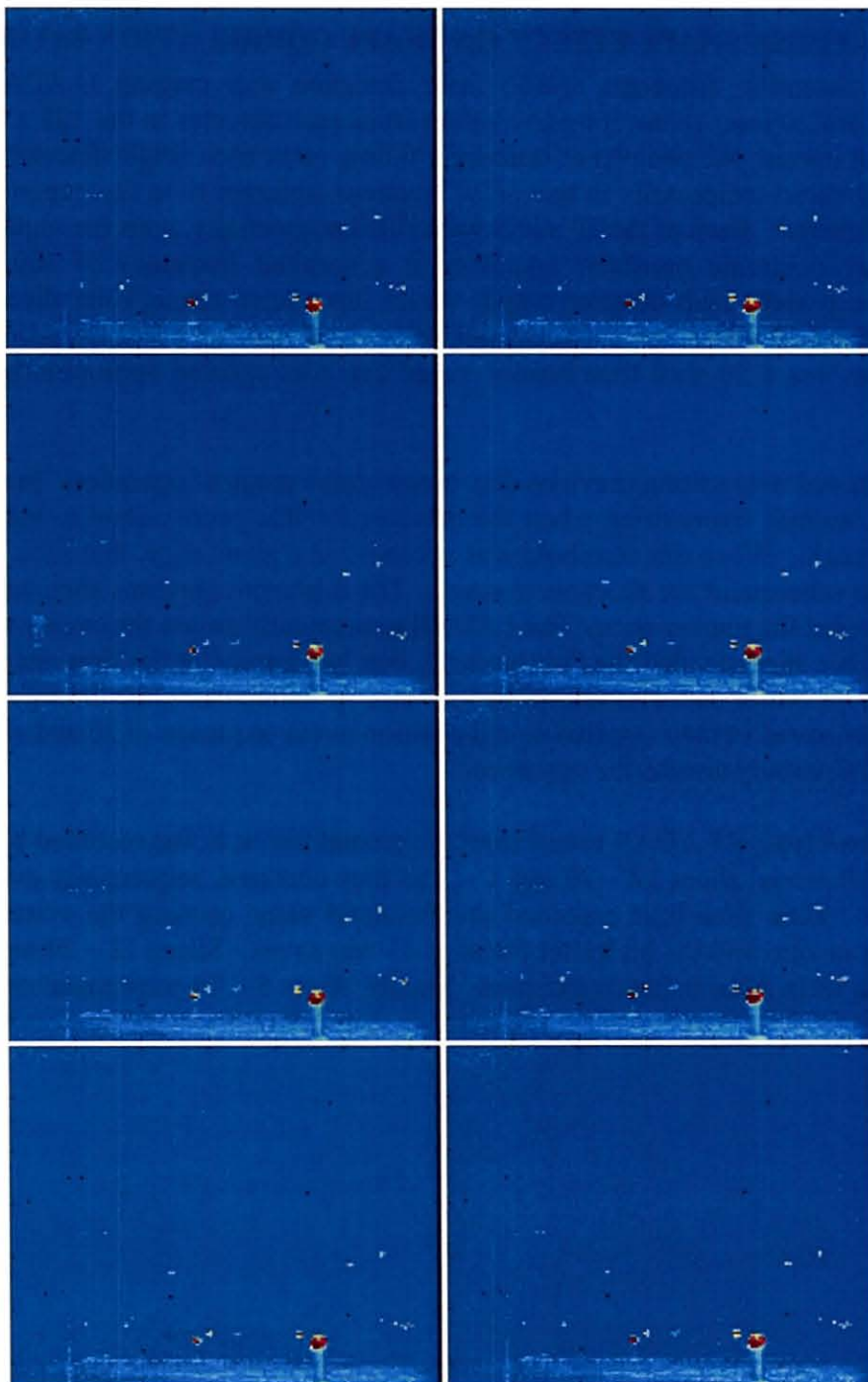Figure A-1: Typical SULAR mode images gathered during the ground test

Figure A-2: Typical trigger mode images gathered during the ground test

APPENDIX B - PULSE SHAPE EFFECT ON SHAPE CORRELATION ESTIMATION

The Advanced Scientific Concepts (ASC) laser detection and ranging (LADAR) had the capability to record 20 laser return intensity values from each detector in the 128 x 128 detector array. In a given instant, the photons of laser light falling upon each single detector were output as a voltage and stored temporarily in one of 20 locations (referred to in this report as "slices"), allotted to that detector. Each of the 20 slices were filled sequentially, with the sequencing being controlled by an electronic oscillator operating at a nominal frequency of 400 mega-Hertz (MHz). As time passed, each detector output values that cycled through the slices, overwrote values that occurred 20 slices ago but kept track of the total number of slices recorded. At any given time, there was a 20 slice time history stored that was updated approximately every 2.4 nanoseconds.

The LADAR stopped overwriting previous data based on the mode of operation. In stop-mode, a particular pixel stopped overwriting when the detector for that pixel output a voltage above a pre-defined threshold. When this threshold was exceeded in a given slice, that slice, the previous 12 slices and the subsequent six slices were saved. The thirteenth previous slice was set to zero value and was called the marker slice. The LADAR permanently stored the twenty slices as well as the total number slices (called the "hit buffer"), that had passed at the time the marker slice was saved. The hit buffer could be related to the range to the marker slice through the speed of light. Slices were saved in their original stored position in the sequence of 20 and almost always wrapped around circularly around the sequence.

Figure B-1 shows a typical LADAR return from the ground test as it was recorded by the system. First, the LADAR stored slices 12 – 20 and 1 – 3 as they occurred, sequentially overwriting the previous values. Then slice four exceeded the threshold value causing the system to trigger. Slice 11 was set to zero and the hit buffer for slice 11 was saved. Slices 12 – 20 and 1 – 3 were saved preventing them from being overwritten. Finally, slices 5 – 10 were saved sequentially as they occurred.
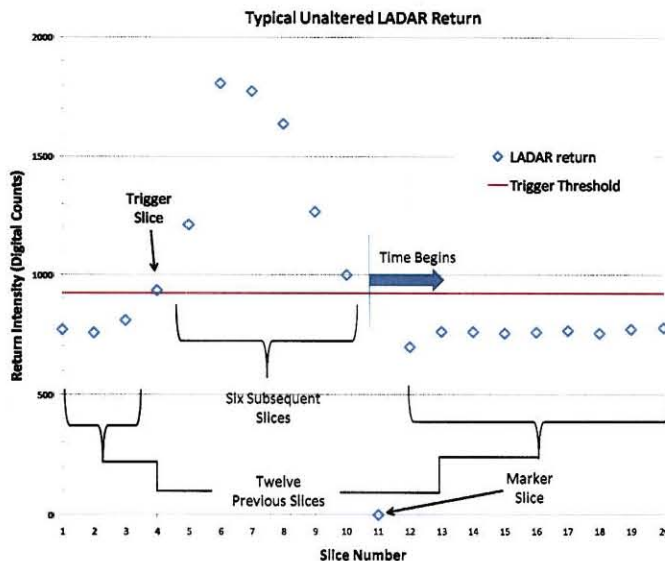
Figure B-1: Typical unaltered LADAR return
recorded during the ground test

In staring underwater laser ranging (SULAR) mode all pixels stopped overwriting simultaneously after a pre-determined amount of time had passed after the emission of the outgoing pulse. The format of the recorded data was identical to that shown in figure B-1, however the marker slice and hence the 19 slices leading up to it were placed based on time and not triggered off of a set threshold.

The first step to analyzing the return waveforms by the normalized variable shaping (NOVAS) range estimation algorithm was to shift the points circularly such that the marker slice became the first slice and the remaining 19 slices appeared in chronological order. Next, the slices saved on either side of the marker slice were thrown out as they were corrupted by an anomaly in the LADAR system as a side-effect of creating the marker slice. Figure B-2 shows several representative waveforms gathered during the ground test that have been shifted in this manner and have the corrupted data points marked. All three waveforms in figure B-2 triggered in slice 14. The minimum intensity pulse triggered at the peak such that the six subsequent slices captured the entire pulse shape. The maximum intensity pulse triggered very early in the rise of the pulse such that the trailing edge of the pulse was not recorded. This was a factor for ranging algorithms like NOVAS that used pulse shape correlation to determine the target range.

The NOVAS algorithm modeled the return LADAR pulse as a piecewise continuous joining of two Gaussian shaped pulses of different widths. The left half from negative infinity to the pulse peak was a Gaussian pulse of one width, while the right half from the pulse peak to positive infinity was a Gaussian pulse of another width. The NOVAS then attempted to match the position of the peak as well as the left and right pulse widths to find the combination with the highest correlation. The resulting peak location within a given frame of 20 slices, plus the total range to the marker slice range would then become the NOVAS estimation for the target range. The NOVAS range estimation was generated under the assumption that the peak of the true LADAR return pulse marked the target range.
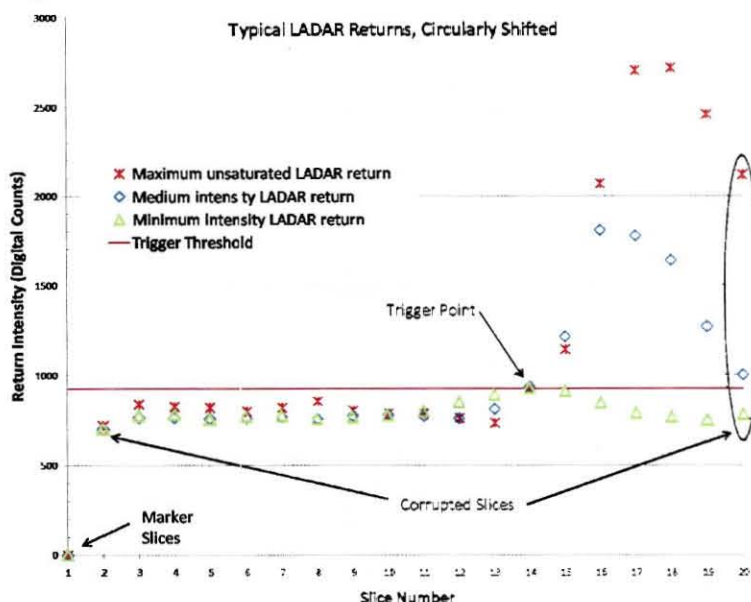
Figure B-2: Typical LADAR returns recorded
during the ground test, circularly shifted

The goal of the NOVAS algorithm was to produce an estimation of the true LADAR return pulse while reducing the effect of random noise in the signal. The received signal was subject to several noise sources including the photonic effects of shot noise and Poisson noise, as well as system effects of thermal noise and quantization error during an analog to digital conversion. To eliminate the effect of any bias in the signal and to generate consistently sized NOVAS estimations, LADAR return pulses were first normalized by subtracting the remaining 17 slices from their mean and dividing by their standard deviation.

The mechanism by which the LADAR stored the waveforms limited the utility of a shape correlating range estimator by truncating the trailing half of the return pulse for all returns except those just greater than threshold. Figure B-3 shows the same three waveforms after they were normalized as well as the NOVAS estimation for each of the pulse shapes. It can be seen that for the minimal intensity return, both the left and right halves of the pulse had numerous values upon which to perform the correlation, resulting in a more accurate solution. The medium intensity return had only three points on the right half of the curve, while the maximum intensity return had only two points on the right half of the curve.

The fewer number of points made the shape matching very susceptible to variation due to noise in the signal. For example, shifting the far right point on the maximum intensity curve would cause a significant change in the shape of the right half of the matched pulse and a shift in the matched peak. Shifting a single point on the minimum intensity return had a lesser effect on the pulse shape and peak location due to the larger number of points acting to reduce the effect of random noise. Waveforms that captured the entire left and right halves provided the best conditions for countering the effect of noise, generating an accurate estimation of the true pulse, and providing an accurate range estimation.
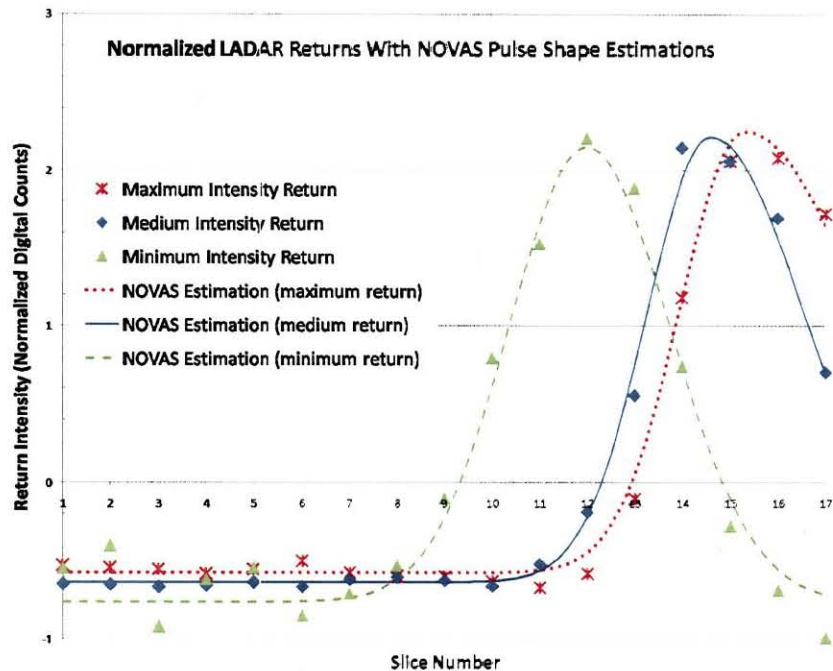
Figure B-3: Normalized LADAR returns gathered during the
ground test with NOVAS pulse shaped estimations

Modifying the trigger logic such that it saves more slices after the trigger point and fewer prior to the trigger point would alleviate this problem. Swapping the methodology such that only six slices prior to trigger and twelve slices after were saved would ensure that even the largest pulses were captured in their entirety. Another option would be to raise the threshold such that large pulses trigger later on the rising side, extending the six subsequent frames nearer to the trailing edge of the pulse. However, this would decrease the overall sensitivity and only gain at most two additional slices on the back side of the pulse.

Detector saturation also reduced the accuracy of the NOVAS estimator or any other shape correlator. Each pixel in the detector array was unable to accurately report return values greater than approximately 2,900 digital counts. Instead the pixel would report some maximum level with a significant amount of system induced variability. This would deform the peak of the pulse into a jagged plateau, eliminating any useful information about the position of the true peak. In most cases the saturated waveforms captured by the LADAR did not include any information past the plateau due to the triggering mechanism already addressed. Figure B-4 shows an example of such a saturated waveform with the NOVAS estimation of the pulse. It can be seen that the NOVAS model did not fit well with the saturated pulse, and that the peak of the pulse had been spread across a plateau that covers four slices, or approximately five feet. Saturated pulses indicated range errors of up to two feet less than actual target range.
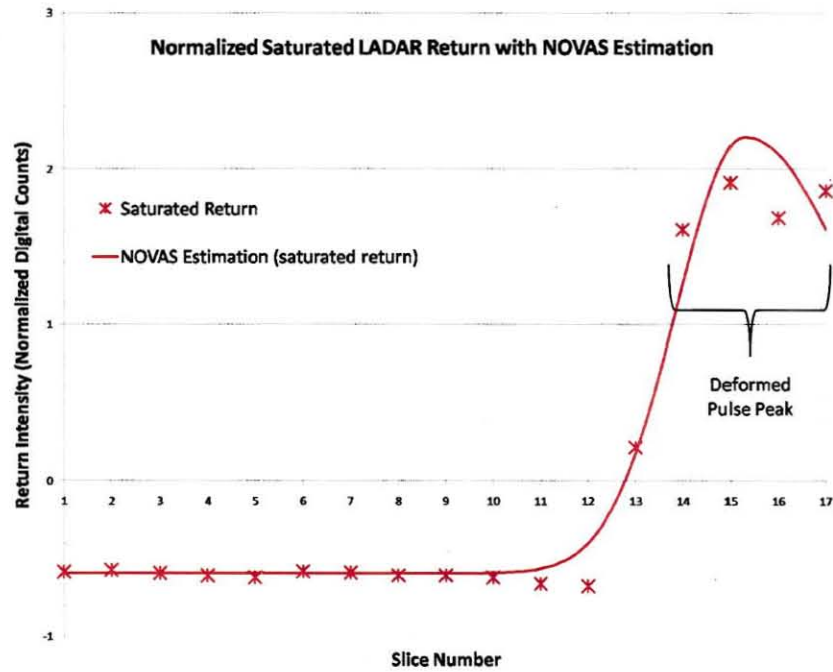
Figure B-4: Normalized saturated LADAR return gathered during
the ground test, with NOVAS estimation

APPENDIX C - LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Definition
AAR	air-to-air refueling
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
ASC	Advanced Scientific Concepts
DGPS	differential global positioning system
EMI/C	electro-magnetic interference and compatibility
FLVC	FLASH LADAR Video Camera
FOV	field of view
GAINR-LITE	GPS aided internal navigation reference
GPS	global positioning system
LADAR	laser detection and ranging
LIL RASCAL	LADAR Internally Loaded RASCAL
MFD	multi-function display
MHz	mega-Hertz
mJ	milli-Joule
mm	millimeter
MOS	modification operational supplement
NOVAS	normalized variable shaping
ns	nanoseconds
RASCAL	Reconfigurable Airborne Sensor, Communications and Laser
RMSE	root mean squared error
SULAR	staring underwater laser ranging
TIM	technical information memorandum
TMP	test management project
TPS	Test Pilot School
TV	television
TW	Test Wing
μm	micrometer
UAV	unmanned aerial vehicle
USAF	United States Air Force

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